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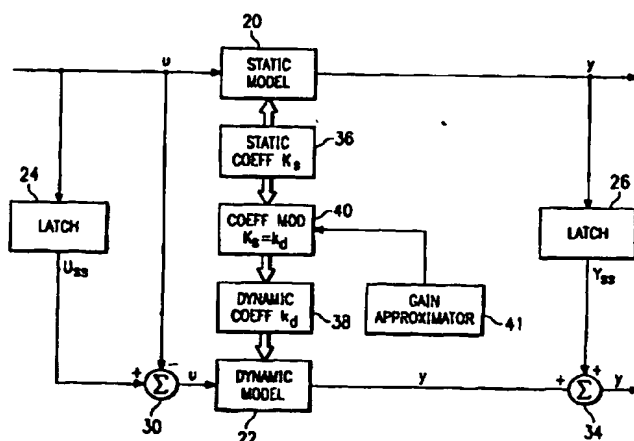
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INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification 6 : G05B 17/02		A1	(11) International Publication Number: WO 97/42553
			(43) International Publication Date: 13 November 1997 (13.11.97)
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(54) Title: METHOD AND APPARATUS FOR MODELING DYNAMIC AND STEADY-STATE PROCESSES FOR PREDICTION, CONTROL AND OPTIMIZATION



(57) Abstract

A method for providing independent static and dynamic models in a prediction, control and optimization environment utilizes an independent static model (20) and an independent dynamic model (22). The static model (20) is a rigorous predictive model that is trained over a wide range of data, whereas the dynamic model (22) is trained over a narrow range of data. The gain K of the static model (20) is utilized to scale the gain k of the dynamic model (22). The forced dynamic portion of the model (22) referred to as the b_i variables are scaled by the ratio of the gains K and k . The b_i have a direct effect on the gain of a dynamic model (22). This is facilitated by a coefficient modification block (40). Thereafter, the difference between the new value input to the static model (20) and the prior steady-state value is utilized as an input to the dynamic model (22). The predicted dynamic output is then summed with the previous steady-state value to provide a predicted value Y . Additionally, the path that is traversed between steady-state value changes.

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IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

**METHOD AND APPARATUS FOR MODELING DYNAMIC AND
STEADY-STATE PROCESSES FOR PREDICTION, CONTROL AND
OPTIMIZATION**

TECHNICAL FIELD OF THE INVENTION

The present invention pertains in general to modeling techniques and, more particularly, to combining steady-state and dynamic models for the purpose of prediction, control and optimization.

BACKGROUND OF THE INVENTION

Process models that are utilized for prediction, control and optimization can be divided into two general categories, steady-state models and dynamic models. In each case the model is a mathematical construct that characterizes the process, and process measurements are utilized to parameterize or fit the model so that it replicates the behavior of the process. The mathematical model can then be implemented in a simulator for prediction or inverted by an optimization algorithm for control or optimization.

Steady-state or static models are utilized in modern process control systems that usually store a great deal of data, this data typically containing steady-state information at many different operating conditions. The steady-state information is utilized to train a non-linear model wherein the process input variables are represented by the vector U that is processed through the model to output the dependent variable Y . The non-linear model is a steady-state phenomenological or empirical model developed utilizing several ordered pairs (U_i, Y_i) of data from different measured steady states. If a model is represented as:

$$Y = P(U, Y) \quad (1)$$

where P is some parameterization, then the steady-state modeling procedure can be presented as:

$$(\vec{U}, \vec{Y}) \rightarrow P \quad (2)$$

where U and Y are vectors containing the U_i, Y_i ordered pair elements. Given the model P , then the steady-state process gain can be calculated as:

$$K = \frac{\Delta P(U, Y)}{\Delta U} \quad (3)$$

The steady-state model therefore represents the process measurements that are taken when the system is in a "static" mode. These measurements do not account for the perturbations that exist when changing from one steady-state condition to another steady-state condition. This is referred to as the dynamic part of a model.

5 A dynamic model is typically a linear model and is obtained from process measurements which are not steady-state measurements; rather, these are the data obtained when the process is moved from one steady-state condition to another steady-state condition. This procedure is where a process input or manipulated variable $u(t)$ is input to a process with a process output or controlled variable $y(t)$ being output and measured. Again, ordered pairs of measured data ($u(I)$, $y(I)$) can be utilized to parameterize a phenomenological or empirical model, this time the data coming from non-steady-state operation. The dynamic model is represented as:

$$y(t) = p(u(t), y(t)) \quad (4)$$

where p is some parameterization. Then the dynamic modeling procedure can be represented as:

$$(\vec{u}, \vec{y}) \sim p \quad (5)$$

Where u and y are vectors containing the ($u(I)$, $y(I)$) ordered pair elements. Given the model p , then the steady-state gain of a dynamic model can be calculated as:

$$k = \frac{\Delta p(u, y)}{\Delta u} \quad (6)$$

Unfortunately, almost always the dynamic gain k does not equal the steady-state gain K , since the steady-state gain is modeled on a much larger set of data, whereas the dynamic gain is defined around a set of operating conditions wherein an existing set of operating conditions are mildly perturbed. This results in a shortage of sufficient non-linear information in the dynamic data set in which non-linear information is contained within the static model. Therefore, the gain of the system may not be adequately modeled for an existing set of steady-state operating conditions. Thus, when considering two independent models, one for

the steady-state model and one for the dynamic model, there is a mis-match between the gains of the two models when used for prediction, control and optimization. The reason for this mis-match are that the steady-state model is non-linear and the dynamic model is linear, such that the gain of the steady-state model changes depending on the process operating point, with the gain of the linear model being fixed. Also, the data utilized to parameterize the dynamic model do not represent the complete operating range of the process, i.e., the dynamic data is only valid in a narrow region. Further, the dynamic model represents the acceleration properties of the process (like inertia) whereas the steady-state model represents the tradeoffs that determine the process final resting value (similar to the tradeoff between gravity and drag that determines terminal velocity in free fall).

One technique for combining non-linear static models and linear dynamic models is referred to as the Hammerstein model. The Hammerstein model is basically an input-output representation that is decomposed into two coupled parts. This utilizes a set of intermediate variables that are determined by the static models which are then utilized to construct the dynamic model. These two models are not independent and are relatively complex to create.

SUMMARY OF THE INVENTION

The present invention disclosed and claimed herein comprises a method and apparatus for controlling the operation of a plant by predicting a change in the dynamic input values to the plant to effect a change in the output from a current output value at a first time to a desired output value at a second time. The controller includes a dynamic predictive model for receiving the current input value and the desired output value and predicting a plurality of input values at different time positions between the first time and the second time to define a dynamic operation path of the plant between the current output value and the desired output value at the second time. An optimizer then optimizes the operation of the dynamic controller at each of the different time positions from the first time to the second time in accordance with a predetermined optimization method that optimizes the objectives of the dynamic controller to achieve a desired path. This allows the objectives of the dynamic predictive model to vary as a function of time.

In another aspect of the present invention, the dynamic model includes a dynamic forward model operable to receive input values at each of the time positions and map the received input values through a stored representation of the plant to provide a predicted dynamic output value. An error generator then compares the predicted dynamic output value to the desired output value and generates a primary error value as a difference therebetween for each of the time positions. An error minimization device then determines a change in the input value to minimize the primary error value output by the error generator. A summation device sums the determined input change value with the original input value for each time position to provide a future input value, with a controller controlling the operation of the error minimization device and the optimizer. This minimizes the primary error value in accordance with the predetermined optimization method.

In a yet another aspect of the present invention, the controller is operable to control the summation device to iteratively minimize the primary error value by storing the summed output value from the summation device in a first pass through the error minimization device and then input the latch contents to the dynamic forward model in subsequent passes and for a plurality of subsequent passes. The output of the error minimization device is then summed with the previous contents of the latch, the latch containing the current value of the input on the first pass through the dynamic forward model and the error minimization device. The controller outputs the contents of the latch as the input to the plant after the primary error value has been determined to meet the objectives in accordance with the predetermined optimization method.

In a further aspect of the present invention, a gain adjustment device is provided to adjust the gain of the linear model for substantially all of the time positions. This gain adjustment device includes a non-linear model for receiving an input value and mapping the received input value through a stored representation of the plant to provide on the output thereof a predicted output value, and having a non-linear gain associated therewith. The linear model has parameters associated therewith that define the dynamic gain thereof with a parameter adjustment device then adjusting the parameters of the linear model as a function of the gain of the non-linear model for at least one of the time positions.

In yet a further aspect of the present invention, the gain adjustment device further allows for approximation of the dynamic gain for a plurality of the time positions between the value of the dynamic gain at the first time and the determined dynamic gain at one of the time positions having the dynamic gain thereof determined by the parameter adjustment device. This one time position is the maximum of the time positions at the second time.

In yet another aspect of the present invention, the error minimization device includes a primary error modification device for modifying the primary error to provide a modified error value. The error minimization device optimizes the operation of the dynamic controller to minimize the modified error value in

accordance with the predetermined optimization method. The primary error is weighted as a function of time from the first time to the second time, with the weighting function decreasing as a function of time such that the primary error value is attenuated at a relatively high value proximate to the first time and
5 attenuated at a relatively low level proximate to the second time.

In yet a further aspect of the present invention, a predictive system is provided for predicting the operation of a plant with the predictive system having an input for receiving input value and an output for providing a predicted output value. The system includes a non-linear model having an input for receiving the
10 input value and mapping it across a stored learned representation of the plant to provide a predicted output. The non-linear model has an integrity associated therewith that is a function of a training operation that varies across the mapped space. A first principles model is also provided for providing a calculator representation of the plant. A domain analyzer determines when the input value
15 falls within a region of the mapped space having an integrity associated therewith that is less than a predetermined integrity threshold. A domain switching device is operable to switch operation between the non-linear model and the first principles model as a function of the determined integrity level comparison with the predetermined threshold. If it is above the integrity threshold, the non-linear
20 model is utilized and, if it is below the integrity threshold, the first principles model is utilized.

BRIEF DESCRIPTION OF THE DRAWINGS

For a more complete understanding of the present invention and the advantages thereof, reference is now made to the following description taken in conjunction with the accompanying Drawings in which:

- 5 FIGURE 1 illustrates a prior art Hammerstein model;
- FIGURE 2 illustrates a block diagram of the modeling technique of the present invention;
- FIGURE 3a-3d illustrate timing diagrams for the various outputs of the system of FIGURE 2;
- 10 FIGURE 4 illustrates a detailed block diagram of the dynamic model utilizing the identification method;
- FIGURE 5 illustrates a block diagram of the operation of the model of FIGURE 4;
- FIGURE 6 illustrates an example of the modeling technique of the present invention utilized in a control environment;
- 15 FIGURE 7 illustrates a diagrammatic view of a change between two steady-state values;
- FIGURE 8 illustrates a diagrammatic view of the approximation algorithm for changes in the steady-state value;
- 20 FIGURE 9 illustrates a block diagram of the dynamic model;
- FIGURE 10 illustrates a detail of the control network utilizing the error constraining algorithm of the present invention;
- FIGURES 11a and 11b illustrate plots of the input and output during optimization;
- 25 FIGURE 12 illustrates a plot depicting desired and predicted behavior;
- FIGURE 13 illustrates various plots for controlling a system to force the predicted behavior to the desired behavior;
- FIGURE 14 illustrates a plot of the trajectory weighting algorithm of the present invention;
- 30 FIGURE 15 illustrates a plot for the constraining algorithm;
- FIGURE 16 illustrates a plot of the error algorithm as a function of time;

FIGURE 17 illustrates a flowchart depicting the statistical method for generating the filter and defining the end point for the constraining algorithm of FIGURE 15;

FIGURE 18 illustrates a diagrammatic view of the optimization process;

5 FIGURE 18a illustrates a diagrammatic representation of the manner in which the path between steady-state values is mapped through the input and output space;

FIGURE 19 illustrates a flowchart for the optimization procedure;

10 FIGURE 20 illustrates a diagrammatic view of the input space and the error associated therewith;

FIGURE 21 illustrates a diagrammatic view of the confidence factor in the input space;

FIGURE 22 illustrates a block diagram of the method for utilizing a combination of a non-linear system and a first principal system; and

15 FIGURE 23 illustrates an alternate embodiment of the embodiment of FIGURE 22.

DETAILED DESCRIPTION OF THE INVENTION

Referring now to FIGURE 1, there is illustrated a diagrammatic view of a Hammerstein model of the prior art. This is comprised of a non-linear static operator model 10 and a linear dynamic model 12, both disposed in a series configuration. The operation of this model is described in *H.T. Su, and T.J. McAvoy*, "Integration of Multilayer Perceptron Networks and Linear Dynamic Models: A Hammerstein Modeling Approach" to appear in *I & EC Fundamentals*, paper dated July 7, 1992, which reference is incorporated herein by reference. Hammerstein models in general have been utilized in modeling non-linear systems for some time. The structure of the Hammerstein model illustrated in FIGURE 1 utilizes the non-linear static operator model 10 to transform the input U into intermediate variables H. The non-linear operator is usually represented by a finite polynomial expansion. However, this could utilize a neural network or any type of compatible modeling system. The linear dynamic operator model 12 could utilize a discrete dynamic transfer function representing the dynamic relationship between the intermediate variable H and the output Y. For multiple input systems, the non-linear operator could utilize a multilayer neural network, whereas the linear operator could utilize a two layer neural network. A neural network for the static operator is generally well known and described in U.S. Patent No. 5,353,207, issued October 4, 1994, and assigned to the present assignee, which is incorporated herein by reference. These type of networks are typically referred to as a multilayer feed-forward network which utilizes training in the form of back-propagation. This is typically performed on a large set of training data. Once trained, the network has weights associated therewith, which are stored in a separate database.

Once the steady-state model is obtained, one can then choose the output vector from the hidden layer in the neural network as the intermediate variable for the Hammerstein model. In order to determine the input for the linear dynamic operator, $u(t)$, it is necessary to scale the output vector $h(d)$ from the non-linear static operator model 10 for the mapping of the intermediate variable $h(t)$ to the

output variable of the dynamic model $y(t)$, which is determined by the linear dynamic model.

5 During the development of a linear dynamic model to represent the linear dynamic operator, in the Hammerstein model, it is important that the steady-state non-linearity remain the same. To achieve this goal, one must train the dynamic model subject to a constraint so that the non-linearity learned by the steady-state model remains unchanged after the training. This results in a dependency of the two models on each other.

10 Referring now to FIGURE 2, there is illustrated a block diagram of the modeling method of the present invention, which is referred to as a systematic modeling technique. The general concept of the systematic modeling technique in the present invention results from the observation that, while process gains (steady-state behavior) vary with U 's and Y 's, (i.e., the gains are non-linear), the process dynamics seemingly vary with time only, (i.e., they can be modeled as
15 locally linear, but time-varied). By utilizing non-linear models for the steady-state behavior and linear models for the dynamic behavior, several practical advantages result. They are as follows:

1. Completely rigorous models can be utilized for the steady-state part. This provides a credible basis for economic optimization.
- 20 2. The linear models for the dynamic part can be updated on-line, i.e., the dynamic parameters that are known to be time-varying can be adapted slowly.
3. The gains of the dynamic models and the gains of the steady-state models can be forced to be consistent ($k=K$).

25 With further reference to FIGURE 2, there are provided a static or steady-state model 20 and a dynamic model 22. The static model 20, as described above, is a rigorous model that is trained on a large set of steady-state data. The static model 20 will receive a process input U and provide a predicted output Y .
30 These are essentially steady-state values. The steady-state values at a given time are latched in various latches, an input latch 24 and an output latch 26. The latch

24 contains the steady-state value of the input U_{ss} , and the latch 26 contains the steady-state output value Y_{ss} . The dynamic model 22 is utilized to predict the behavior of the plant when a change is made from a steady-state value of Y_{ss} to a new value Y . The dynamic model 22 receives on the input the dynamic input value u and outputs a predicted dynamic value y . The value u is comprised of the difference between the new value U and the steady-state value in the latch 24, U_{ss} . This is derived from a subtraction circuit 30 which receives on the positive input thereof the output of the latch 24 and on the negative input thereof the new value of U . This therefore represents the delta change from the steady-state. Similarly, on the output the predicted overall dynamic value will be the sum of the output value of the dynamic model, y , and the steady-state output value stored in the latch 26, Y_{ss} . These two values are summed with a summing block 34 to provide a predicted output Y . The difference between the value output by the summing junction 34 and the predicted value output by the static model 20 is that the predicted value output by the summing junction 20 accounts for the dynamic operation of the system during a change. For example, to process the input values that are in the input vector U by the static model 20, the rigorous model, can take significantly more time than running a relatively simple dynamic model. The method utilized in the present invention is to force the gain of the dynamic model 22 k_d to equal the gain K_{ss} of the static model 20.

In the static model 20, there is provided a storage block 36 which contains the static coefficients associated with the static model 20 and also the associated gain value K_{ss} . Similarly, the dynamic model 22 has a storage area 38 that is operable to contain the dynamic coefficients and the gain value k_d . One of the important aspects of the present invention is a link block 40 that is operable to modify the coefficients in the storage area 38 to force the value of k_d to be equal to the value of K_{ss} . Additionally, there is an approximation block 41 that allows approximation of the dynamic gain k_d between the modification updates.

SYSTEMATIC MODEL

The linear dynamic model 22 can generally be represented by the following equations:

$$\delta y(t) = \sum_{i=1}^n b_i \delta u(t - d - i) - \sum_{i=1}^n a_i \delta y(t - i) \quad (7)$$

where:

$$\delta y(t) = y(t) - Y_{ss} \quad (8)$$

$$\delta u(t) = u(t) - u_{ss} \quad (9)$$

5 and t is time, a_i and b_i are real numbers, d is a time delay, $u(t)$ is an input and $y(t)$ an output. The gain is represented by:

$$\frac{y(B)}{u(B)} = k = \frac{(\sum_{i=1}^n b_i B^{i-1}) B^d}{1 + \sum_{i=1}^n a_i B^{i-1}} \quad (10)$$

10 where B is the backward shift operator $B(x(t))=x(t-1)$, t =time, the a_i and b_i are real numbers, I is the number of discrete time intervals in the dead-time of the process, and n is the order of the model. This is a general representation of a linear dynamic model, as contained in *George E.P. Box and G.M. Jenkins, "TIME SERIES ANALYSIS forecasting and control", Holden-Day, San Francisco, 1976, Section 10.2, Page 345.* This reference is incorporated herein by reference.

The gain of this model can be calculated by setting the value of B equal to a value of "1". The gain will then be defined by the following equation:

$$\left[\frac{Y(B)}{U(B)} \right]_{B=1} = k_d = \frac{\sum_{i=1}^n b_i}{1 + \sum_{i=1}^n a_i} \quad (11)$$

The a_i contain the dynamic signature of the process, its unforced, natural response characteristic. They are independent of the process gain. The b_i contain part of the dynamic signature of the process; however, they alone contain the result of the forced response. The b_i determine the gain k of the dynamic model.

5 See: *J.L. Shearer, A.T. Murphy, and H.H. Richardson*, "Introduction to System Dynamics", Addison-Wesley, Reading, Massachusetts, 1967, Chapter 12. This reference is incorporated herein by reference.

10 Since the gain K_{ss} of the steady-state model is known, the gain k_d of the dynamic model can be forced to match the gain of the steady-state model by scaling the b_i parameters. The values of the static and dynamic gains are set equal with the value of b_i scaled by the ratio of the two gains:

$$(b_i)_{scaled} = (b_i)_{old} \left(\frac{K_{ss}}{k_d} \right) \quad (12)$$

$$(b_i)_{scaled} = \frac{(b_i)_{old} K_{ss} \left(1 + \sum_{i=1}^n a_i \right)}{\sum_{i=1}^n b_i} \quad (13)$$

This makes the dynamic model consistent with its steady-state counterpart.

Therefore, each time the steady-state value changes, this corresponds to a gain K_{ss} of the steady-state model. This value can then be utilized to update the gain k_d of the dynamic model and, therefore, compensate for the errors associated with the
15 dynamic model wherein the value of k_d is determined based on perturbations in the

plant on a given set of operating conditions. Since all operating conditions are not modeled, the step of varying the gain will account for changes in the steady-state starting points.

Referring now to FIGURES 3a-3d, there are illustrated plots of the system operating in response to a step function wherein the input value U changes from a value of 100 to a value of 110. In FIGURE 3a, the value of 100 is referred to as the previous steady-state value U_{ss} . In FIGURE 3b, the value of u varies from a value of 0 to a value of 10, this representing the delta between the steady-state value of U_{ss} to the level of 110, represented by reference numeral 42 in FIGURE 3a. Therefore, in FIGURE 3b the value of u will go from 0 at a level 44, to a value of 10 at a level 46. In FIGURE 3c, the output Y is represented as having a steady-state value Y_{ss} of 4 at a level 48. When the input value U rises to the level 42 with a value of 110, the output value will rise. This is a predicted value. The predicted value which is the proper output value is represented by a level 50, which level 50 is at a value of 5. Since the steady-state value is at a value of 4, this means that the dynamic system must predict a difference of a value of 1. This is represented by FIGURE 3d wherein the dynamic output value y varies from a level 54 having a value of 0 to a level 56 having a value of 1.0. However, without the gain scaling, the dynamic model could, by way of example, predict a value for y of 1.5, represented by dashed level 58, if the steady-state values were outside of the range in which the dynamic model was trained. This would correspond to a value of 5.5 at a level 60 in the plot of FIGURE 3c. It can be seen that the dynamic model merely predicts the behavior of the plant from a starting point to a stopping point, not taking into consideration the steady-state values. It assumes that the steady-state values are those that it was trained upon. If the gain k_d were not scaled, then the dynamic model would assume that the steady-state values at the starting point were the same that it was trained upon. However, the gain scaling link between the steady-state model and the dynamic model allow the gain to be scaled and the parameter b_i to be scaled such that the dynamic operation is scaled and a more accurate prediction is made which accounts for the dynamic properties of the system.

Referring now to FIGURE 4, there is illustrated a block diagram of a method for determining the parameters a_i , b_i . This is usually achieved through the use of an identification algorithm, which is conventional. This utilizes the $(u(t), y(t))$ pairs to obtain the a_i and b_i parameters. In the preferred embodiment, a recursive identification method is utilized where the a_i and b_i parameters are updated with each new $(u_i(t), y_i(t))$ pair. See: *T. Eykhoff*, "System Identification", John Wiley & Sons, New York, 1974, Pages 38 and 39, *et. seq.*, and *H. Kurz and W. Godecke*, "Digital Parameter-Adaptive Control Processes with Unknown Dead Time", *Automatica*, Vol. 17, No. 1, 1981, pp. 245-252, which references are incorporated herein by reference.

In the technique of FIGURE 4, the dynamic model 22 has the output thereof input to a parameter-adaptive control algorithm block 60 which adjusts the parameters in the coefficient storage block 38, which also receives the scaled values of k , b_i . This is a system that is updated on a periodic basis, as defined by timing block 62. The control algorithm 60 utilizes both the input u and the output y for the purpose of determining and updating the parameters in the storage area 38.

Referring now to FIGURE 5, there is illustrated a block diagram of the preferred method. The program is initiated in a block 68 and then proceeds to a function block 70 to update the parameters a_i , b_i utilizing the $(u(I), y(I))$ pairs. Once these are updated, the program flows to a function block 72 wherein the steady-state gain factor K is received, and then to a function block 74 to set the dynamic gain to the steady state gain, i.e., provide the scaling function described hereinabove. This is performed after the update. This procedure can be used for on-line identification, non-linear dynamic model prediction and adaptive control.

Referring now to FIGURE 6, there is illustrated a block diagram of one application of the present invention utilizing a control environment. A plant 78 is provided which receives input values $u(t)$ and outputs an output vector $y(t)$. The plant 78 also has measurable state variables $s(t)$. A predictive model 80 is provided which receives the input values $u(t)$ and the state variables $s(t)$ in

addition to the output value $y(t)$. The steady-state model 80 is operable to output a predicted value of both $y(t)$ and also of a future input value $u(t+1)$. This constitutes a steady-state portion of the system. The predicted steady-state input value is U_{ss} with the predicted steady-state output value being Y_{ss} . In a conventional control scenario, the steady-state model 80 would receive as an external input a desired value of the output $y^d(t)$ which is the desired value that the overall control system seeks to achieve. This is achieved by controlling a distributed control system (DCS) 86 to produce a desired input to the plant. This is referred to as $u(t+1)$, a future value. Without considering the dynamic response, the predictive model 80, a steady-state model, will provide the steady-state values. However, when a change is desired, this change will effectively be viewed as a "step response".

To facilitate the dynamic control aspect, a dynamic controller 82 is provided which is operable to receive the input $u(t)$, the output value $y(t)$ and also the steady-state values U_{ss} and Y_{ss} and generate the output $u(t+1)$. The dynamic controller effectively generates the dynamic response between the changes, i.e., when the steady-state value changes from an initial steady-state value U_{ss}^i , Y_{ss}^i to a final steady-state value U_{ss}^f , Y_{ss}^f .

During the operation of the system, the dynamic controller 82 is operable in accordance with the embodiment of FIGURE 2 to update the dynamic parameters of the dynamic controller 82 in a block 88 with a gain link block 90, which utilizes the value K_{ss} from a steady-state parameter block in order to scale the parameters utilized by the dynamic controller 82, again in accordance with the above described method. In this manner, the control function can be realized. In addition, the dynamic controller 82 has the operation thereof optimized such that the path traveled between the initial and final steady-state values is achieved with the use of the optimizer 83 in view of optimizer constraints in a block 85. In general, the predicted model (steady-state model) 80 provides a control network function that is operable to predict the future input values. Without the dynamic controller 82, this is a conventional control network which is generally described

in U.S. Patent No. 5,353,207, issued October 4, 1994, to the present assignee, which patent is incorporated herein by reference.

APPROXIMATE SYSTEMATIC MODELING

For the modeling techniques described thus far, consistency between the steady-state and dynamic models is maintained by rescaling the b_i parameters at each time step utilizing equation 13. If the systematic model is to be utilized in a Model Predictive Control (MPC) algorithm, maintaining consistency may be computationally expensive. These types of algorithms are described in *C.E. Garcia, D.M. Prett and M. Morari*. Model predictive control: theory and practice - a survey, *Automatica*, 25:335-348, 1989; *D.E. Seborg, T.F. Edgar, and D.A. Mellichamp*. Process Dynamics and Control. John Wiley and Sons, New York, NY, 1989. These references are incorporated herein by reference. For example, if the dynamic gain k_d is computed from a neural network steady-state model, it would be necessary to execute the neural network module each time the model was iterated in the MPC algorithm. Due to the potentially large number of model iterations for certain MPC problems, it could be computationally expensive to maintain a consistent model. In this case, it would be better to use an approximate model which does not rely on enforcing consistencies at each iteration of the model.

Referring now to FIGURE 7, there is illustrated a diagram for a change between steady state values. As illustrated, the steady-state model will make a change from a steady-state value at a line 100 to a steady-state value at a line 102. A transition between the two steady-state values can result in unknown settings. The only way to insure that the settings for the dynamic model between the two steady-state values, an initial steady-state value K_{ss}^i and a final steady-state gain K_{ss}^f , would be to utilize a step operation, wherein the dynamic gain k_d was adjusted at multiple positions during the change. However, this may be computationally expensive. As will be described hereinbelow, an approximation algorithm is utilized for approximating the dynamic behavior between the two steady-state values utilizing a quadratic relationship. This is defined as a behavior

line 104, which is disposed between an envelope 106, which behavior line 104 will be described hereinbelow.

Referring now to FIGURE 8, there is illustrated a diagrammatic view of the system undergoing numerous changes in steady-state value as represented by a stepped line 108. The stepped line 108 is seen to vary from a first steady-state value at a level 110 to a value at a level 112 and then down to a value at a level 114, up to a value at a level 116 and then down to a final value at a level 118. Each of these transitions can result in unknown states. With the approximation algorithm that will be described hereinbelow, it can be seen that, when a transition is made from level 110 to level 112, an approximation curve for the dynamic behavior 120 is provided. When making a transition from level 114 to level 116, an approximation gain curve 124 is provided to approximate the steady state gains between the two levels 114 and 116. For making the transition from level 116 to level 118, an approximation gain curve 126 for the steady-state gain is provided. It can therefore be seen that the approximation curves 120-126 account for transitions between steady-state values that are determined by the network, it being noted that these are approximations which primarily maintain the steady-state gain within some type of error envelope, the envelope 106 in FIGURE 7.

The approximation is provided by the block 41 noted in FIGURE 2 and can be designed upon a number of criteria, depending upon the problem that it will be utilized to solve. The system in the preferred embodiment, which is only one example, is designed to satisfy the following criteria:

1. **Computational Complexity:** The approximate systematic model will be used in a Model Predictive Control algorithm, therefore, it is required to have low computational complexity.
2. **Localized Accuracy:** The steady-state model is accurate in localized regions. These regions represent the steady-state operating regimes of the process. The steady-state model is significantly less accurate outside these localized regions.
3. **Final Steady-State:** Given a steady-state set point change, an optimization algorithm which uses the steady-state model will be

used to compute the steady-state inputs required to achieve the set point. Because of item 2, it is assumed that the initial and final steady-states associated with a set-point change are located in regions accurately modeled by the steady-state model.

5 Given the noted criteria, an approximate systematic model can be constructed by enforcing consistency of the steady-state and dynamic model at the initial and final steady-state associated with a set point change and utilizing a linear approximation at points in between the two steady-states. This approximation guarantees that the model is accurate in regions where the steady-state model is well known and utilizes a linear approximation in regions where the steady-state
10 model is known to be less accurate. In addition, the resulting model has low computational complexity. For purposes of this proof, Equation 13 is modified as follows:

$$b_{i, scaled} = \frac{b_i K_{ss} (u(t - d - 1)) (1 + \sum_{i=1}^n a_i)}{\sum_{i=1}^n b_i} \quad (14)$$

15 This new equation 14 utilizes $K_{ss}(u(t-d-1))$ instead of $K_{ss}(u(t))$ as the consistent gain, resulting in a systematic model which is delay invariant.

20 The approximate systematic model is based upon utilizing the gains associated with the initial and final steady-state values of a set-point change. The initial steady-state gain is denoted K_{ss}^i while the initial steady-state input is given by U_{ss}^i . The final steady-state gain is K_{ss}^f and the final input is U_{ss}^f . Given these values, a linear approximation to the gain is given by:

$$K_{ss} (u(t)) = K_{ss}^i + \frac{K_{ss}^f - K_{ss}^i}{U_{ss}^f - U_{ss}^i} (u(t) - U_{ss}^i). \quad (15)$$

Substituting this approximation into Equation 13 and replacing $u(t - d - 1) - u^i$ by $\delta u(t - d - 1)$ yields:

$$\tilde{b}_{j, scaled} = \frac{b_j K_{ss}^i \left(1 + \sum_{i=1}^n a_i \right)}{\sum_{i=1}^n b_i} + \frac{1}{2} \frac{b_j \left(1 + \sum_{i=1}^n a_i \right) (K_{ss}^f - K_{ss}^i)}{\left(\sum_{i=1}^n b_i \right) (U_{ss}^f - U_{ss}^i)} \delta u(t - d - i) \quad (16)$$

To simplify the expression, define the variable \bar{b}_j as:

$$\bar{b}_j = \frac{b_j K_{ss}^i \left(1 + \sum_{i=1}^n a_i \right)}{\sum_{i=1}^n b_i} \quad (17)$$

and g_j as:

$$g_j = \frac{b_j \left(1 + \sum_{i=1}^n a_i \right) (K_{ss}^f - K_{ss}^i)}{\left(\sum_{i=1}^n b_i \right) (U_{ss}^f - U_{ss}^i)} \quad (18)$$

Equation 16 may be written as:

$$\tilde{b}_{j, scaled} = \bar{b}_j + g_j \delta u(t - d - i). \quad (19)$$

Finally, substituting the scaled \tilde{b} 's back into the original difference Equation 7, the following expression for the approximate systematic model is obtained:

$$\delta y(t) = \sum_{i=1}^n \bar{b}_i \delta u(t - d - i) + \sum_{i=1}^n g_i \delta u(t - d - i^2) \delta u(t - d - i) - \sum_{i=1}^n a_i \delta y(t - i) \quad (20)$$

The linear approximation for gain results in a quadratic difference equation for the output. Given Equation 20, the approximate systematic model is shown to be of

low computational complexity. It may be used in a MPC algorithm to efficiently compute the required control moves for a transition from one steady-state to another after a set-point change. Note that this applies to the dynamic gain variations between steady-state transitions and not to the actual path values.

5 CONTROL SYSTEM ERROR CONSTRAINTS

Referring now to FIGURE 9, there is illustrated a block diagram of the prediction engine for the dynamic controller 82 of FIGURE 6. The prediction engine is operable to essentially predict a value of $y(t)$ as the predicted future value $y(t+1)$. Since the prediction engine must determine what the value of the output $y(t)$ is at each future value between two steady-state values, it is necessary to perform these in a "step" manner. Therefore, there will be k steps from a value of zero to a value of N , which value at $k=N$ is the value at the "horizon", the desired value. This, as will be described hereinbelow, is an iterative process, it being noted that the terminology for " $(t+1)$ " refers to an incremental step, with an incremental step for the dynamic controller being smaller than an incremented step for the steady-state model. For the steady-state model, " $y(t+N)$ " for the dynamic model will be, " $y(t+1)$ " for the steady state. The value $y(t+1)$ is defined as follows:

$$y(t+1) = a_1 y(t) + a_2 y(t-1) + b_1 u(t-d-1) + b_2 u(t-d-2) \quad (21)$$

With further reference to FIGURE 9, the input values $u(t)$ for each (u,y) pair are input to a delay line 140. The output of the delay line provides the input value $u(t)$ delayed by a delay value " d ". There are provided only two operations for multiplication with the coefficients b_1 and b_2 , such that only two values $u(t)$ and $u(t-1)$ are required. These are both delayed and then multiplied by the coefficients b_1 and b_2 and then input to a summing block 141. Similarly, the output value $y^p(t)$ is input to a delay line 142, there being two values required for multiplication with the coefficients a_1 and a_2 . The output of this multiplication is then input to the summing block 141. The input to the delay line 142 is either the actual input value $y^p(t)$ or the iterated output value of the summation block 141, which is the previous value computed by the dynamic controller 82. Therefore,

the summing block 141 will output the predicted value $y(t+1)$ which will then be input to a multiplexor 144. The multiplexor 144 is operable to select the actual output $y^d(t)$ on the first operation and, thereafter, select the output of the summing block 141. Therefore, for a step value of $k=0$ the value $y^d(t)$ will be selected by the multiplexor 144 and will be latched in a latch 145. The latch 145 will provide the predicted value $y^p(t+k)$ on an output 146. This is the predicted value of $y(t)$ for a given k that is input back to the input of delay line 142 for multiplication with the coefficients a_1 and a_2 . This is iterated for each value of k from $k=0$ to $k=N$.

The a_1 and a_2 values are fixed, as described above, with the b_1 and b_2 values scaled. This scaling operation is performed by the coefficient modification block 38. However, this only defines the beginning steady-state value and the final steady-state value, with the dynamic controller and the optimization routines described in the present application defining how the dynamic controller operates between the steady-state values and also what the gain of the dynamic controller is. The gain specifically is what determines the modification operation performed by the coefficient modification block 38.

In FIGURE 9, the coefficients in the coefficient modification block 38 are modified as described hereinabove with the information that is derived from the steady-state model. The steady-state model is operated in a control application, and is comprised in part of a forward steady-state model 141 which is operable to receive the steady-state input value $U_{ss}(t)$ and predict the steady-state output value $Y_{ss}(t)$. This predicted value is utilized in an inverse steady-state model 143 to receive the desired value $y^d(t)$ and the predicted output of the steady-state model 141 and predict a future steady-state input value or manipulated value $U_{ss}(t+N)$ and also a future steady-state input value $Y_{ss}(t+N)$ in addition to providing the steady-state gain K_{ss} . As described hereinabove, these are utilized to generate scaled b -values. These b -values are utilized to define the gain k_d of the dynamic model. In can therefore be seen that this essentially takes a linear dynamic model with a fixed gain and allows it to have a gain thereof modified by a non-linear model as the operating point is moved through the output space.

Referring now to FIGURE 10, there is illustrated a block diagram of the dynamic controller and optimizer. The dynamic controller includes a dynamic model 149 which basically defines the predicted value $y^p(k)$ as a function of the inputs $y(t)$, $s(t)$ and $u(t)$. This was essentially the same model that was described hereinabove with reference to FIGURE 9. The model 149 predicts the output values $y^p(k)$ between the two steady-state values, as will be described hereinbelow. The model 149 is predefined and utilizes an identification algorithm to identify the a_1 , a_2 , b_1 and b_2 coefficients during training. Once these are identified in a training and identification procedure, these are "fixed". However, as described hereinabove, the gain of the dynamic model is modified by scaling the coefficients b_1 and b_2 . This gain scaling is not described with respect to the optimization operation of FIGURE 10, although it can be incorporated in the optimization operation.

The output of model 149 is input to the negative input of a summing block 150. Summing block 150 sums the predicted output $y^p(k)$ with the desired output $y^d(t)$. In effect, the desired value of $y^d(t)$ is effectively the desired steady-state value Y^f , although it can be any desired value. The output of the summing block 150 comprises an error value which is essentially the difference between the desired value $y^d(t)$ and the predicted value $y^p(k)$. The error value is modified by an error modification block 151, as will be described hereinbelow, in accordance with error modification parameters in a block 152. The modified error value is then input to an inverse model 153, which basically performs an optimization routine to predict a change in the input value $u(t)$. In effect, the optimizer 153 is utilized in conjunction with the model 149 to minimize the error output by summing block 150. Any optimization function can be utilized, such as a Monte Carlo procedure. However, in the present invention, a gradient calculation is utilized. In the gradient method, the gradient $\partial(y)/\partial(u)$ is calculated and then a gradient solution performed as follows:

$$\Delta u_{new} = \Delta u_{old} + \left(\frac{\partial(y)}{\partial(u)} \right) \times E \quad (22)$$

The optimization function is performed by the inverse model 153 in accordance with optimization constraints in a block 154. An iteration procedure is performed with an iterate block 155 which is operable to perform an iteration with the combination of the inverse model 153 and the predictive model 149 and output on an output line 156 the future value $u(t+k+1)$. For $k=0$, this will be the initial steady-state value and for $k=N$, this will be the value at the horizon, or at the next steady-state value. During the iteration procedure, the previous value of $u(t+k)$ has the change value Δu added thereto. This value is utilized for that value of k until the error is within the appropriate levels. Once it is at the appropriate level, the next $u(t+k)$ is input to the model 149 and the value thereof optimized with the iterate block 155. Once the iteration procedure is done, it is latched. As will be described hereinbelow, this is a combination of modifying the error such that the actual error output by the block 150 is not utilized by the optimizer 153 but, rather, a modified error is utilized. Alternatively, different optimization constraints can be utilized, which are generated by the block 154, these being described hereinbelow.

Referring now to FIGURES 11a and 11b, there are illustrated plots of the output $y(t+k)$ and the input $u_k(t+k+1)$, for each k from the initial steady-state value to the horizon steady-state value at $k=N$. With specific reference to FIGURE 11a, it can be seen that the optimization procedure is performed utilizing multiple passes. In the first pass, the actual value $u^*(t+k)$ for each k is utilized to determine the values of $y(t+k)$ for each u, y pair. This is then accumulated and the values processed through the inverse model 153 and the iterate block 155 to minimize the error. This generates a new set of inputs $u_k(t+k+1)$ illustrated in FIGURE 11b. Therefore, the optimization after pass 1 generates the values of $u(t+k+1)$ for the second pass. In the second pass, the values are again optimized in accordance with the various constraints to again generate another set of values for $u(t+k+1)$. This continues until the overall objective function is reached. This objective function is a combination of the operations as a function of the error and the operations as a function of the constraints, wherein the optimization constraints may control the overall operation of the inverse model 153 or the error

modification parameters in block 152 may control the overall operation. Each of the optimization constraints will be described in more detail hereinbelow.

Referring now to FIGURE 12, there is illustrated a plot of $y^d(t)$ and $y^p(t)$.

5 The predicted value is represented by a waveform 170 and the desired output is represented by a waveform 172, both plotted over the horizon between an initial steady-state value Y_{ss}^i and a final steady-state value Y_{ss}^f . It can be seen that the desired waveform prior to $k=0$ is substantially equal to the predicted output. At $k=0$, the desired output waveform 172 raises its level, thus creating an error. It
10 can be seen that at $k=0$, the error is large and the system then must adjust the manipulated variables to minimize the error and force the predicted value to the desired value. The objective function for the calculation of error is of the form:

$$\min_{\Delta u_i} \sum_j \sum_k (A_j * (\bar{y}^p(t) - \bar{y}^d(t))^2) \quad (23)$$

where: Δu_i is the change in input variable (IV) i at time interval i

A_j is the weight factor for control variable (CV) j

15 $y^p(t)$ is the predicted value of CV j at time interval k

$y^d(t)$ is the desired value of CV j .

Trajectory Weighting

The present system utilizes what is referred to as "trajectory weighting" which encompasses the concept that one does not put a constant degree of importance on the future predicted process behavior matching the desired behavior at every future time set, i.e., at low k-values. One approach could be that one is more tolerant of error in the near term (low k-values) than farther into the future (high k-values). The basis for this logic is that the final desired behavior is more important than the path taken to arrive at the desired behavior, otherwise the path traversed would be a step function. This is illustrated in FIGURE 13 wherein three possible predicted behaviors are illustrated, one represented by a curve 174 which is acceptable, one is represented by a different curve 176, which is also acceptable and one represented by a curve 178, which is unacceptable since it goes above the desired level on curve 172. Curves 174-178 define the desired behavior over the horizon for $k=1$ to N .

In Equation 23, the predicted curves 174-178 would be achieved by forcing the weighting factors A_j to be time varying. This is illustrated in FIGURE 14. In FIGURE 14, the weighting factor A as a function of time is shown to have an increasing value as time and the value of k increases. This results in the errors at the beginning of the horizon (low k-values) being weighted much less than the errors at the end of the horizon (high k-values). The result is more significant than merely redistributing the weights out to the end of the control horizon at $k=N$. This method also adds robustness, or the ability to handle a mismatch between the process and the prediction model. Since the largest error is usually experienced at the beginning of the horizon, the largest changes in the independent variables will also occur at this point. If there is a mismatch between the process and the prediction (model error), these initial moves will be large and somewhat incorrect, which can cause poor performance and eventually instability. By utilizing the trajectory weighting method, the errors at the beginning of the horizon are weighted less, resulting in smaller changes in the independent variables and, thus, more robustness.

Error Constraints

Referring now to FIGURE 15, there are illustrated constraints that can be placed upon the error. There is illustrated a predicted curve 180 and a desired curve 182, desired curve 182 essentially being a flat line. It is desirable for the error between curve 180 and 182 to be minimized. Whenever a transient occurs at $t=0$, changes of some sort will be required. It can be seen that prior to $t=0$, curve 182 and 180 are substantially the same, there being very little error between the two. However, after some type of transition, the error will increase. If a rigid solution were utilized, the system would immediately respond to this large error and attempt to reduce it in as short a time as possible. However, a constraint frustum boundary 184 is provided which allows the error to be large at $t=0$ and reduces it to a minimum level at a point 186. At point 186, this is the minimum error, which can be set to zero or to a non-zero value, corresponding to the noise level of the output variable to be controlled. This therefore encompasses the same concepts as the trajectory weighting method in that final future behavior is considered more important than near term behavior. The ever shrinking minimum and/or maximum bounds converge from a slack position at $t=0$ to the actual final desired behavior at a point 186 in the constraint frustum method.

The difference between constraint frustums and trajectory weighting is that constraint frustums are an absolute limit (hard constraint) where any behavior satisfying the limit is just as acceptable as any other behavior that also satisfies the limit. Trajectory weighting is a method where differing behaviors have graduated importance in time. It can be seen that the constraints provided by the technique of FIGURE 15 requires that the value $y^p(t)$ is prevented from exceeding the constraint value. Therefore, if the difference between $y^d(t)$ and $y^p(t)$ is greater than that defined by the constraint boundary, then the optimization routine will force the input values to a value that will result in the error being less than the constraint value. In effect, this is a "clamp" on the difference between $y^p(t)$ and $y^d(t)$. In the trajectory weighting method, there is no "clamp" on the difference therebetween; rather, there is merely an attenuation factor placed on the error before input to the optimization network.

Trajectory weighting can be compared with other methods, there being two methods that will be described herein, the dynamic matrix control (DMC) algorithm and the identification and command (IdCom) algorithm. The DMC algorithm utilizes an optimization to solve the control problem by minimizing the objective function:

$$\min_{\Delta U_d} \sum_j \sum_k (A_j * (\bar{y}^P(t) - \bar{y}^D(t)) + \sum_i B_i * \sum_l (\Delta U_{il})^2) \quad (24)$$

where B_i is the move suppression factor for input variable i . This is described in *Cutler, C.R. and B.L. Ramaker, Dynamic Matrix Control - A Computer Control Algorithm, AIChE National Meeting, Houston, TX (April, 1979)*, which is incorporated herein by reference.

It is noted that the weights A_j and desired values $y^d(t)$ are constant for each of the control variables. As can be seen from Equation 24, the optimization is a trade off between minimizing errors between the control variables and their desired values and minimizing the changes in the independent variables. Without the move suppression term, the independent variable changes resulting from the set point changes would be quite large due to the sudden and immediate error between the predicted and desired values. Move suppression limits the independent variable changes, but for all circumstances, not just the initial errors.

The IdCom algorithm utilizes a different approach. Instead of a constant desired value, a path is defined for the control variables to take from the current value to the desired value. This is illustrated in FIGURE 16. This path is a more gradual transition from one operation point to the next. Nevertheless, it is still a rigidly defined path that must be met. The objective function for this algorithm takes the form:

$$\min_{\Delta U_d} \sum_j \sum_k (A_j * (Y^{P,k} - y_{ref,k}))^2 \quad (25)$$

This technique is described in *Richalet, J., A. Rault, J.L. Testud, and J. Papon, Model Predictive Heuristic Control: Applications to Industrial Processes, Automatica, 14, 413-428 (1978)*, which is incorporated herein by reference. It should be noted that the requirement of Equation 25 at each time interval is sometimes difficult. In fact, for control variables that behave similarly, this can result in quite erratic independent variable changes due to the control algorithm attempting to endlessly meet the desired path exactly.

Control algorithms such as the DMC algorithm that utilize a form of matrix inversion in the control calculation, cannot handle control variable hard constraints directly. They must treat them separately, usually in the form of a steady-state linear program. Because this is done as a steady-state problem, the constraints are time invariant by definition. Moreover, since the constraints are not part of a control calculation, there is no protection against the controller violating the hard constraints in the transient while satisfying them at steady-state.

With further reference to FIGURE 15, the boundaries at the end of the envelope can be defined as described hereinbelow. One technique described in the prior art, *W. Edwards Deming, "Out of the Crisis,"* Massachusetts Institute of Technology, Center for Advanced Engineering Study, Cambridge Mass., Fifth Printing, September 1988, pages 327-329, describes various Monte Carlo experiments that set forth the premise that any control actions taken to correct for common process variation actually may have a negative impact, which action may work to increase variability rather than the desired effect of reducing variation of the controlled processes. Given that any process has an inherent accuracy, there should be no basis to make a change based on a difference that lies within the accuracy limits of the system utilized to control it. At present, commercial controllers fail to recognize the fact that changes are undesirable, and continually adjust the process, treating all deviation from target, no matter how small, as a special cause deserving of control actions, *i.e.*, they respond to even minimal changes. Over adjustment of the manipulated variables therefore will result, and increase undesirable process variation. By placing limits on the error with the present filtering algorithms described herein, only controller actions that are

proven to be necessary are allowed, and thus, the process can settle into a reduced variation free from unmerited controller disturbances. The following discussion will deal with one technique for doing this, this being based on statistical parameters.

5 Filters can be created that prevent model-based controllers from taking any action in the case where the difference between the controlled variable measurement and the desired target value are not significant. The significance level is defined by the accuracy of the model upon which the controller is statistically based. This accuracy is determined as a function of the standard
10 deviation of the error and a predetermined confidence level. The confidence level is based upon the accuracy of the training. Since most training sets for a neural network-based model will have "holes" therein, this will result in inaccuracies within the mapped space. Since a neural network is an empirical model, it is only as accurate as the training data set. Even though the model may not have been
15 trained upon a given set of inputs, it will extrapolate the output and predict a value given a set of inputs, even though these inputs are mapped across a space that is questionable. In these areas, the confidence level in the predicted output is relatively low. This is described in detail in U. S. patent application Serial No. 08/025,184, filed March 2, 1993, which is incorporated herein by reference.

20 Referring now to FIGURE 17, there is illustrated a flowchart depicting the statistical method for generating the filter and defining the end point 186 in FIGURE 15. The flowchart is initiated at a start block 200 and then proceeds to a function block 202, wherein the control values $u(t+1)$ are calculated. However, prior to acquiring these control values, the filtering operation must be processed.
25 The program will flow to a function block 204 to determine the accuracy of the controller. This is done off-line by analyzing the model predicted values compared to the actual values, and calculating the standard deviation of the error in areas where the target is undisturbed. The model accuracy of $e_m(t)$ is defined as follows:

$$e_m(t) = a(t) - p(t) \quad (26)$$

calculate the running accumulation of errors. This is formed utilizing a CUSUM approach. The controller CUSUM calculations are done as follows:

$$S_{low} = \min (0, S_{low}(t-1) + d(t) - m(t) - \Sigma(m) + k) \quad (29)$$

$$S_{hi} = \max (0, S_{hi}(t-1) + [d(t) - m(t) - \Sigma(m)] - k) \quad (30)$$

where: S_{hi} = Running Positive Qsum

S_{low} = Running Negative Qsum

k = Tuning factor - minimal detectable change threshold

with the following defined:

Hq = significance level. Values of (j,k) can be found so that the CUSUM control chart will have significance levels equivalent to Shewhart control charts.

- 10 The program will then flow to a decision block 214 to determine if the CUSUM limits check out, i.e., it will determine if the Qsum values are within the limits. If the Qsum, the accumulated sum error, is within the established limits, the program will then flow along the "Y" path. And, if it is not within the limits, it will flow along the "N" path to accept the controller values $u(t+1)$. The limits are
- 15 determined if both the value of $S_{hi} \geq +1 * Hq$ and $S_{low} \leq -1 * Hq$. Both of these actions will result in this program flowing along the "Y" path. If it flows along the "N" path, the sum is set equal to zero and then the program flows to the function block 210. If the Qsum values are within the limits, it flows along the "Y" path to a function block 218 wherein a determination is made as to whether the user
- 20 wishes to perturb the process. If so, the program will flow along the "Y" path to the function block 210 to accept the control values $u(t+1)$. If not, the program will flow along the "N" path from decision block 218 to a function block 222 to suppress the controller values $u(t+1)$. The decision block 218, when it flows along the "Y" path, is a process that allows the user to re-identify the model for

on-line adaptation, i.e., retrain the model. This is for the purpose of data collection and once the data has been collected, the system is then reactivated.

Referring now to FIGURE 18, there is illustrated a block diagram of the overall optimization procedure. In the first step of the procedure, the initial steady-state values $\{Y_{ss}^i, U_{ss}^i\}$ and the final steady-state values $\{Y_{ss}^f, U_{ss}^f\}$ are determined, as defined in blocks 226 and 228, respectively. In some calculations, both the initial and the final steady-state values are required. The initial steady-state values are utilized to define the coefficients a^i, b^i in a block 228. As described above, this utilizes the coefficient scaling of the b-coefficients.

Similarly, the steady-state values in block 228 are utilized to define the coefficients a^f, b^f , it being noted that only the b-coefficients are also defined in a block 229. Once the beginning and end points are defined, it is then necessary to determine the path therebetween. This is provided by block 230 for path optimization. There are two methods for determining how the dynamic controller traverses this path. The first, as described above, is to define the approximate dynamic gain over the path from the initial gain to the final gain. As noted above, this can incur some instabilities. The second method is to define the input values over the horizon from the initial value to the final value such that the desired value Y_{ss}^f is achieved. Thereafter, the gain can be set for the dynamic model by scaling the b-coefficients. As noted above, this second method does not necessarily force the predicted value of the output $y^p(t)$ along a defined path; rather, it defines the characteristics of the model as a function of the error between the predicted and actual values over the horizon from the initial value to the final or desired value. This effectively defines the input values for each point on the trajectory or, alternatively, the dynamic gain along the trajectory.

Referring now to FIGURE 18a, there is illustrated a diagrammatic representation of the manner in which the path is mapped through the input and output space. The steady-state model is operable to predict both the output steady-state value Y_{ss}^i at a value of $k=0$, the initial steady-state value, and the output steady-state value Y_{ss}^f at a time $t+N$ where $k=N$, the final steady-state value. At the initial steady-state value, there is defined a region 227, which region

227 comprises a surface in the output space in the proximity of the initial steady-state value, which initial steady-state value also lies in the output space. This defines the range over which the dynamic controller can operate and the range over which it is valid. At the final steady-state value, if the gain were not changed,
5 the dynamic model would not be valid. However, by utilizing the steady-state model to calculate the steady-state gain at the final steady-state value and then force the gain of the dynamic model to equal that of the steady-state model, the dynamic model then becomes valid over a region 229, proximate the final steady-state value. This is at a value of $k=N$. The problem that arises is how to define
10 the path between the initial and final steady-state values. One possibility, as mentioned hereinabove, is to utilize the steady-state model to calculate the steady-state gain at multiple points along the path between the initial steady-state value and the final steady-state value and then define the dynamic gain at those points. This could be utilized in an optimization routine, which could require a large
15 number of calculations. If the computational ability were there, this would provide a continuous calculation for the dynamic gain along the path traversed between the initial steady-state value and the final steady-state value utilizing the steady-state gain. However, it is possible that the steady-state model is not valid in regions between the initial and final steady-state values, i.e., there is a low
20 confidence level due to the fact that the training in those regions may not be adequate to define the model therein. Therefore, the dynamic gain is approximated in these regions, the primary goal being to have some adjustment of the dynamic model along the path between the initial and the final steady-state values during the optimization procedure. This allows the dynamic operation of
25 the model to be defined. This is represented by a number of surfaces 225 as shown in phantom.

Referring now to FIGURE 19, there is illustrated a flow chart depicting the optimization algorithm. The program is initiated at a start block 232 and then
30 proceeds to a function block 234 to define the actual input values $u^*(t)$ at the beginning of the horizon, this typically being the steady-state value U_{ss} . The program then flows to a function block 235 to generate the predicted values $y^p(k)$ over the horizon for all k for the fixed input values. The program then flows to a

function block 236 to generate the error $E(k)$ over the horizon for all k for the previously generated $y^p(k)$. These errors and the predicted values are then accumulated, as noted by function block 238. The program then flows to a function block 240 to optimize the value of $u(t)$ for each value of k in one embodiment. This will result in k -values for $u(t)$. Of course, it is sufficient to utilize less calculations than the total k -calculations over the horizon to provide for a more efficient algorithm. The results of this optimization will provide the predicted change $\Delta u(t+k)$ for each value of k in a function block 242. The program then flows to a function block 243 wherein the value of $u(t+k)$ for each u will be incremented by the value $\Delta u(t+k)$. The program will then flow to a decision block 244 to determine if the objective function noted above is less than or equal to a desired value. If not, the program will flow back along an "N" path to the input of function block 235 to again make another pass. This operation was described above with respect to FIGURES 11a and 11b. When the objective function is in an acceptable level, the program will flow from decision block 244 along the "Y" path to a function block 245 to set the value of $u(t+k)$ for all u . This defines the path. The program then flows to an End block 246.

Steady State Gain Determination

Referring now to FIGURE 20, there is illustrated a plot of the input space and the error associated therewith. The input space is comprised of two variables x_1 and x_2 . The y-axis represents the function $f(x_1, x_2)$. In the plane of x_1 and x_2 , there is illustrated a region 250, which represents the training data set. Areas outside of the region 250 constitute regions of no data, i.e., a low confidence level region. The function Y will have an error associated therewith. This is represented by a plane 252. However, the error in the plane 250 is only valid in a region 254, which corresponds to the region 250. Areas outside of region 254 on plane 252 have an unknown error associated therewith. As a result, whenever the network is operated outside of the region 250 with the error region 254, the confidence level in the network is low. Of course, the confidence level will not abruptly change once outside of the known data regions but, rather, decreases as the distance from the known data in the training set increases. This is represented in FIGURE 21 wherein the confidence is defined as $\alpha(x)$. It can be seen from FIGURE 21 that the confidence level $\alpha(x)$ is high in regions overlying the region 250.

Once the system is operating outside of the training data regions, i.e., in a low confidence region, the accuracy of the neural net is relatively low. In accordance with one aspect of the preferred embodiment, a first principles model $g(x)$ is utilized to govern steady-state operation. The switching between the neural network model $f(x)$ and the first principle models $g(x)$ is not an abrupt switching but, rather, it is a mixture of the two.

The steady-state gain relationship is defined in Equation 7 and is set forth in a more simple manner as follows:

$$K(\bar{u}) = \frac{\partial (f(\bar{u}))}{\partial (\bar{u})} \quad (31)$$

A new output function $Y(u)$ is defined to take into account the confidence factor $\alpha(u)$ as follows:

$$Y(\bar{u}) = \alpha(\bar{u}) \cdot f(\bar{u}) + (1 - \alpha(\bar{u})) g(\bar{u}) \quad (32)$$

where: $\alpha(u)$ = confidence in model $f(u)$

$\alpha(u)$ in the range of 0-1

$\alpha(u) \in \{0,1\}$

This will give rise to the relationship:

$$K(\bar{u}) = \frac{\partial(Y(\bar{u}))}{\partial(\bar{u})} \quad (33)$$

- 5 In calculating the steady-state gain in accordance with this Equation utilizing the output relationship $Y(u)$, the following will result:

$$K(\bar{u}) = \frac{\partial(\alpha(\bar{u}))}{\partial(\bar{u})} \times F(\bar{u}) + \alpha(\bar{u}) \frac{\partial(F(\bar{u}))}{\partial(\bar{u})} + \frac{\partial(1 - \alpha(\bar{u}))}{\partial(\bar{u})} \times g(\bar{u}) + (1 - \alpha(\bar{u})) \frac{\partial(g(\bar{u}))}{\partial(\bar{u})} \quad (34)$$

- Referring now to FIGURE 22, there is illustrated a block diagram of the embodiment for realizing the switching between the neural network model and the first principles model. A neural network block 300 is provided for the function $f(u)$, a first principle block 302 is provided for the function $g(u)$ and a confidence level block 304 for the function $\alpha(u)$. The input $u(t)$ is input to each of the blocks 300-304. The output of block 304 is processed through a subtraction block 306 to generate the function $1-\alpha(u)$, which is input to a multiplication block 308 for multiplication with the output of the first principles block 302. This provides the function $(1-\alpha(u)) \cdot g(u)$. Additionally, the output of the confidence block 304 is input to a multiplication block 310 for multiplication with the output of the neural network block 300. This provides the function $f(u) \cdot \alpha(u)$. The output of block 308 and the output of block 310 are input to a summation block 312 to provide the output $Y(u)$.

- 20 Referring now to FIGURE 23, there is illustrated an alternate embodiment which utilizes discreet switching. The output of the first principles block 302 and the neural network block 300 are provided and are operable to receive the input $x(t)$. The output of the network block 300 and first principles block 302 are input

Steady State Gain Determination

Referring now to FIGURE 20, there is illustrated a plot of the input space and the error associated therewith. The input space is comprised of two variables x_1 and x_2 . The y-axis represents the function $f(x_1, x_2)$. In the plane of x_1 and x_2 , there is illustrated a region 250, which represents the training data set. Areas outside of the region 250 constitute regions of no data, i.e., a low confidence level region. The function Y will have an error associated therewith. This is represented by a plane 252. However, the error in the plane 250 is only valid in a region 254, which corresponds to the region 250. Areas outside of region 254 on plane 252 have an unknown error associated therewith. As a result, whenever the network is operated outside of the region 250 with the error region 254, the confidence level in the network is low. Of course, the confidence level will not abruptly change once outside of the known data regions but, rather, decreases as the distance from the known data in the training set increases. This is represented in FIGURE 21 wherein the confidence is defined as $\alpha(x)$. It can be seen from FIGURE 21 that the confidence level $\alpha(x)$ is high in regions overlying the region 250.

Once the system is operating outside of the training data regions, i.e., in a low confidence region, the accuracy of the neural net is relatively low. In accordance with one aspect of the preferred embodiment, a first principles model $g(x)$ is utilized to govern steady-state operation. The switching between the neural network model $f(x)$ and the first principle models $g(x)$ is not an abrupt switching but, rather, it is a mixture of the two.

The steady-state gain relationship is defined in Equation 7 and is set forth in a more simple manner as follows:

$$K(\vec{u}) = \frac{\partial (f(\vec{u}))}{\partial (\vec{u})} \quad (31)$$

A new output function $Y(u)$ is defined to take into account the confidence factor $\alpha(u)$ as follows:

$$Y(\bar{u}) = \alpha(\bar{u}) \cdot f(\bar{u}) + (1 - \alpha(\bar{u})) g(\bar{u}) \quad (32)$$

where: $\alpha(u)$ = confidence in model $f(u)$

$\alpha(u)$ in the range of 0-1

$\alpha(u) \in \{0,1\}$

This will give rise to the relationship:

$$K(\bar{u}) = \frac{\partial(Y(\bar{u}))}{\partial(\bar{u})} \quad (33)$$

- 5 In calculating the steady-state gain in accordance with this Equation utilizing the output relationship $Y(u)$, the following will result:

$$K(\bar{u}) = \frac{\partial(\alpha(\bar{u}))}{\partial(\bar{u})} \times F(\bar{u}) + \alpha(\bar{u}) \frac{\partial(F(\bar{u}))}{\partial(\bar{u})} + \frac{\partial(1 - \alpha(\bar{u}))}{\partial(\bar{u})} \times g(\bar{u}) + (1 - \alpha(\bar{u})) \frac{\partial(g(\bar{u}))}{\partial(\bar{u})} \quad (34)$$

- Referring now to FIGURE 22, there is illustrated a block diagram of the embodiment for realizing the switching between the neural network model and the first principles model. A neural network block 300 is provided for the function $f(u)$, a first principle block 302 is provided for the function $g(u)$ and a confidence level block 304 for the function $\alpha(u)$. The input $u(t)$ is input to each of the blocks 300-304. The output of block 304 is processed through a subtraction block 306 to generate the function $1-\alpha(u)$, which is input to a multiplication block 308 for multiplication with the output of the first principles block 302. This provides the function $(1-\alpha(u)) \cdot g(u)$. Additionally, the output of the confidence block 304 is input to a multiplication block 310 for multiplication with the output of the neural network block 300. This provides the function $f(u) \cdot \alpha(u)$. The output of block 308 and the output of block 310 are input to a summation block 312 to provide the output $Y(u)$.

- 20 Referring now to FIGURE 23, there is illustrated an alternate embodiment which utilizes discreet switching. The output of the first principles block 302 and the neural network block 300 are provided and are operable to receive the input $x(t)$. The output of the network block 300 and first principles block 302 are input

to a switch 320, the switch 320 operable to select either the output of the first principals block 302 or the output of the neural network block 300. The output of the switch 320 provides the output $Y(u)$.

5 The switch 320 is controlled by a domain analyzer 322. The domain analyzer 322 is operable to receive the input $x(t)$ and determine whether the domain is one that is within a valid region of the network 300. If not, the switch 320 is controlled to utilize the first principles operation in the first principles block 302. The domain analyzer 322 utilizes the training database 326 to determine the regions in which the training data is valid for the network 300. Alternatively, the
10 domain analyzer 320 could utilize the confidence factor $\alpha(u)$ and compare this with a threshold, below which the first principles model 302 would be utilized.

15 Although the preferred embodiment has been described in detail, it should be understood that various changes, substitutions and alterations can be made therein without departing from the spirit and scope of the invention as defined by the appended claims.

WHAT IS CLAIMED IS:

1. A dynamic controller for controlling the operation of the plant by predicting a change in the dynamic input values to the plant to effect a change in the output from a current output value at a first time to a desired output value at a second time, comprising:
- 5 a dynamic predictive model for receiving the current input value and the desired output value and predicting a plurality of input values at different time positions between the first time and the second time to define a dynamic operation path of the plant between the current output value and the desired output value at the second time; and
- 10 an optimizer for optimizing the operation of the dynamic controller at each of the different time positions from the first time to the second time in accordance with a predetermined optimization method that optimizes the objectives of the dynamic controller to achieve a desired path, such that the objectives of the dynamic predictive model varies as a function of time.
- 15
2. The dynamic controller of Claim 1, wherein said dynamic predictive model comprises:
- a dynamic forward model operable to receive input values at each of said time positions and map said received input values through a stored representation of the plant to provide a predicted dynamic output value;
- 5 an error generator for comparing the predicted dynamic output value to the desired output value and generating a primary error value as the difference therebetween for each of said time positions;
- an error minimization device for determining a change in the input value to minimize the primary error value output by said error generator;
- 10 a summation device for summing said determined input change value with the original input value for each time position to provide a future input value; and

15 a controller for controlling the operation of said error minimization device to operate under control of said optimizer to minimize said primary error value in accordance with said predetermined optimization method.

3. The dynamic controller of Claim 2, wherein said controller controls the operation of said summation device to iteratively minimize said primary error value by storing the summed output from said summation device in a latch in a first pass through said error minimization device and input the latch contents to
5 said dynamic forward model in subsequent pass and for a plurality of subsequent passes, with the output of said error minimization device summed with the previous contents of said latch with said summation device, said latch containing the current value of the input on the first pass through said dynamic forward model and said error minimization device, said controller outputting the contents
10 of said latch as the input to the plant after said primary error value has been determined to meet the objectives in accordance with said predetermined optimization method.

4. The dynamic controller of Claim 2, wherein said dynamic forward model is a dynamic linear model with a fixed gain.

5. The dynamic controller of Claim 4 and further comprising a gain adjustment device for adjusting the gain of said linear model for substantially all of said time positions.

6. The dynamic controller of Claim 5, wherein said gain adjustment device comprises:

5 a non-linear model for receiving an input value and mapping the received input value through a stored representation of the plant to provide on the output thereof a predicted output value, and having a non-linear gain associated therewith;

said linear model having parameters associated therewith that define the dynamic gain thereof, and

10 a parameter adjustment device for adjusting the parameters of said
linear model as a function of the gain of said non-linear model for at least one of
said time positions.

7. The dynamic controller of Claim 6, wherein said gain adjustment
device further comprises an approximation device for approximating the dynamic
gain for a plurality of said time positions between the value of the dynamic gain at
said first time and the determined dynamic gain at the one of said time positions
5 having the dynamic gain thereof determined by said parameter adjustment device.

8. The dynamic controller of Claim 7, wherein the one of said time
positions at which said parameter adjustment device adjusts said parameters as a
function of the gain of said non-linear model corresponds to the maximum at the
second time.

9. The dynamic controller of Claim 6, wherein said non-linear model
is a steady-state model.

10. The dynamic controller of Claim 2, wherein said error minimization
device includes a primary error modification device for modifying said primary
error to provide a modified error value, said error minimization device optimizing
the operation of the dynamic controller to minimize said modified error value in
5 accordance with said predetermined optimization method.

11. The dynamic controller of Claim 10, wherein said primary error is
weighted as a function of time from the first time to the second time.

12. The dynamic controller of Claim 11, wherein said weighting
function decreases as a function of time such that said primary error value is
attenuated at a relatively high value proximate to the first time and attenuated at a
relatively low level proximate to the second time.

13. The dynamic controller of Claim 2, wherein said error minimization device receives said predicted output from said dynamic forward model and determines a change in the input value maintaining a constraint on the predicted output value such that minimization of the primary error value through a
5 determined input change would not cause said predicted output from said dynamic forward model to exceed said constraint.

14. The dynamic controller of Claim 2, and further comprising a filter determining the operation of said error minimization device when the difference between the predicted manipulated variable and the desired output value is insignificant.

15. The dynamic controller of Claim 14, wherein said filter determines when the difference between the predicted manipulated variable and the desired output value is not significant by determining the accuracy of the model upon which the dynamic forward model is based.

16. The dynamic controller of Claim 15, wherein the accuracy is determined as a function of the standard deviation of the error and a predetermined confidence level, wherein said confidence level is based upon the accuracy of the training over the mapped space.

17. A method for predicting an output value from a received input value, comprising the steps of:

5 modeling a set of static data received from a plant in a predictive static model over a first range, the static model having a static gain of K and modeling the static operation of the plant;

modeling a set of dynamic data received from the plant in a predictive dynamic model over a second range smaller than the first range, the dynamic model having a dynamic gain k and modeling the dynamic operation of

10 the plant, and the dynamic model being independent of the operation of the static model;

adjusting the gain of the dynamic model as a predetermined function of the gain of the static model to vary the model parameters of the dynamic model;

15 predicting the dynamic operation of the predicted input value for a change in the input value between a first input value at a first time and a second input value at a second time;

20 subtracting the input value from a steady-state input value previously determined and inputting the difference to the dynamic model and processing the input through the dynamic model to provide a dynamic output value; and

adding the dynamic output value from the dynamic model to a steady-state output value previously determined to provide a predicted value.

18. The method of Claim 17, wherein the predetermined function is an equality function wherein the static gain K is equal to the dynamic gain k .

19. The method of Claim 17, wherein the static model is a non-linear model.

20. The method of Claim 19, wherein the dynamic model for a given dynamic gain is linear.

21. The method of Claim 20, wherein the step of adjusting the gain of the dynamic model as a function of the predetermined function of the gain of the static model is a non-linear operation.

5 22. The method of Claim 17, wherein the static model and the dynamic model are utilized in a control function to receive as inputs the manipulated inputs of the plant, the actual output from the plant in addition to a desired output value at which the plant is to operate, and then perform the step of predicting future manipulated inputs required to achieve the desired output.

23. The method of Claim 22, and further comprising the step of optimizing the operation of the dynamic model in accordance with a predetermined optimization method between an initial steady-state value and a predicted final steady-state value that constitutes an input control variable to the plant during the control operation.

24. The method of Claim 23, wherein the step of optimizing comprises determining the dynamic gain k for multiple positions between the input steady-state input value and the final predicted steady-state input value that comprises the input control values to the plant.

25. The method of Claim 24, wherein the step of determining utilizes an algorithm that estimates the dynamic gain k independent of the operation of the static model.

26. The method of Claim 25, wherein the algorithm is a quadratic equation.

27. The method of Claim 23, wherein the step of predicting with the dynamic model utilized as a dynamic controller comprises the steps of:

predicting the dynamic operation of the plant from the initial steady-state input value to the predicted steady-state input value to provide a predicted dynamic operation;

comparing the predicted dynamic operation to the desired steady-state value at the final desired output value and generating an error as the difference therebetween;

determining a change in the input value for input to step of predicting the dynamic operation which will vary the input value thereto; and varying the change in the input value to minimize the error.

28. The method of Claim 27, wherein the step of determining the error comprises multiplying the determined error value by a predetermined weighting value that is a function of time from the first time to the second time.

29. The method of Claim 27, wherein the predetermined weighting function attenuates the error for values proximate in time to the initial steady-state value at the first time and decreases the attenuation value as time increases to the final steady-state value at the second time.

30. A predictive system for predicting the operation of a plant, the predictive system operable to receive an input value and provide on an output of the predictive system a predicted output value, comprising:

5 a non-linear model having an input for receiving the input value and mapping it across a stored learned representation of the plant to provide the predictive system output on an output, said non-linear model having an internal integrity that is a function of a training operation that varies across the mapped space such that the accuracy of the predicted value will vary as the integrity varies;

10 a first principles model for providing a calculated representation of the plant that is not a function of a training operation;

a domain analyzer for determining when the input value input to said non-linear model falls within a region of the mapped space having an integrity that is less than a predetermined integrity threshold; and

15 a control system for selecting between said non-linear model and said first principles model based upon said domain analyzer determining that the integrity is above or below the predetermined threshold, such that said non-linear model is selected when said integrity is above said threshold and said first principles model is selected when said integrity is below said threshold.

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FIG. 1
(PRIOR ART)

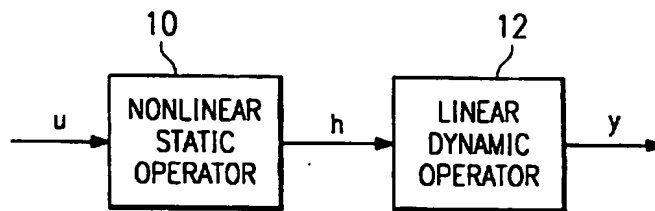


FIG. 2

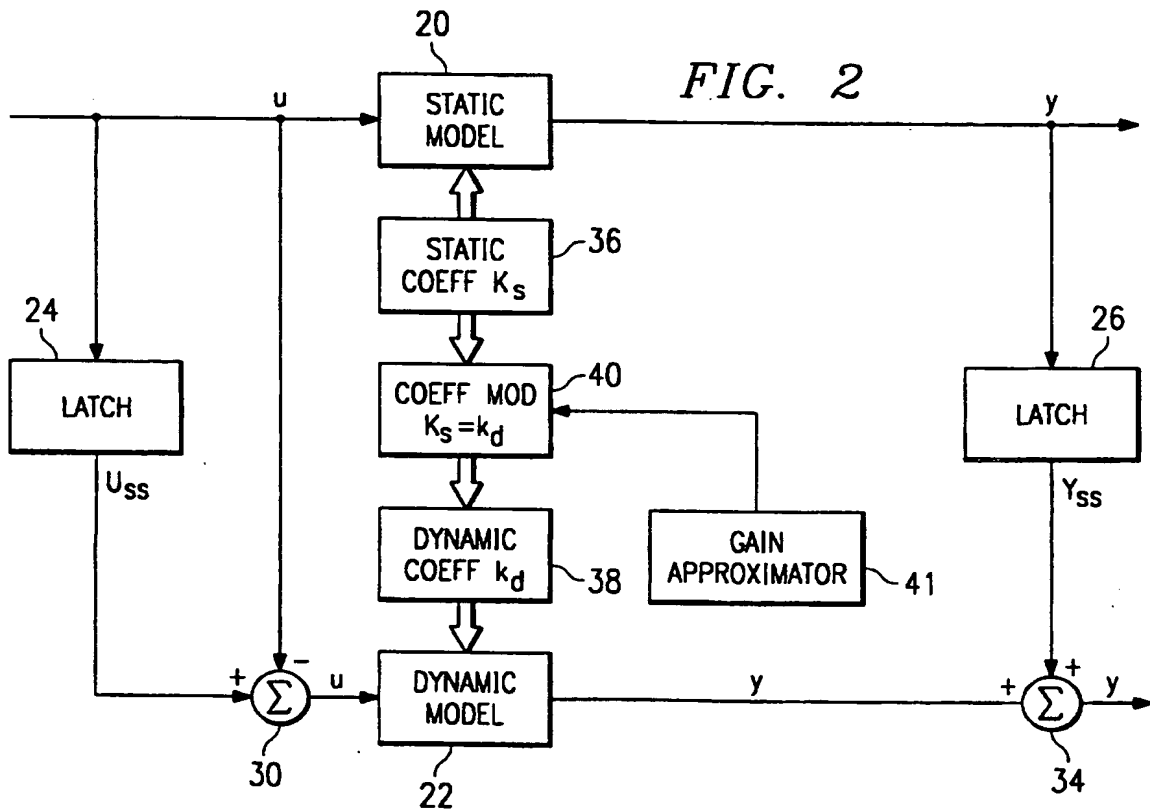


FIG. 4

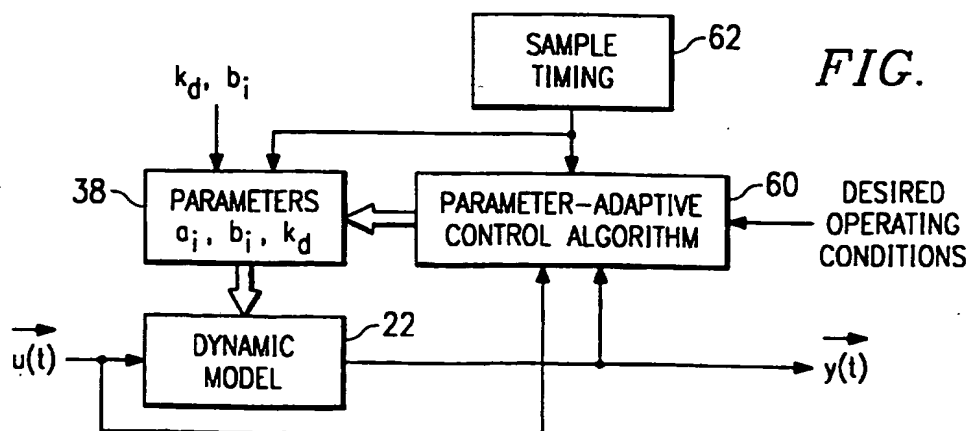


FIG. 3a

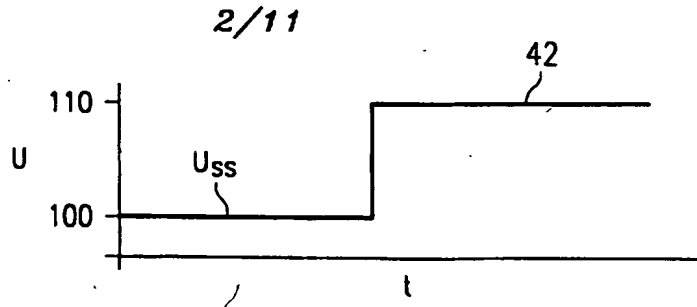


FIG. 3b

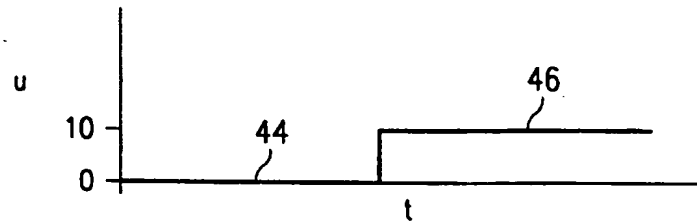


FIG. 3c

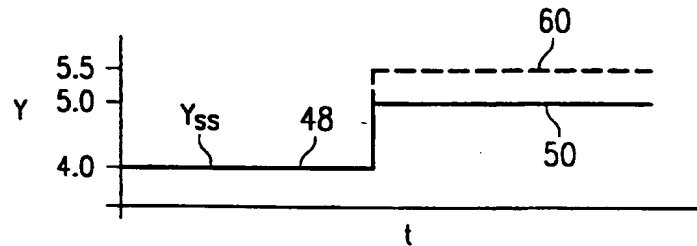


FIG. 3d

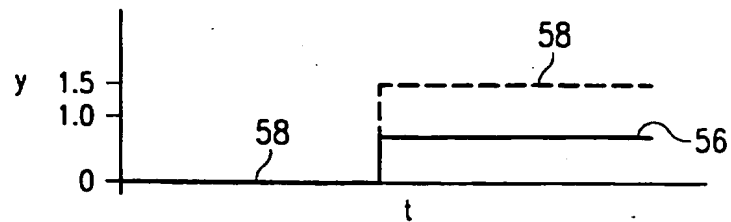
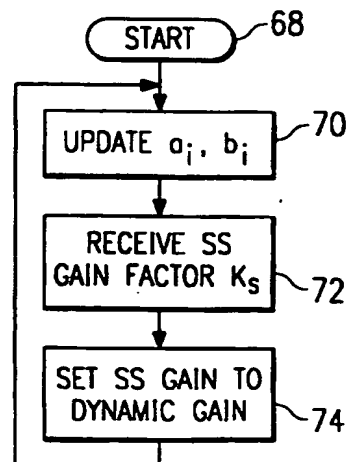


FIG. 5



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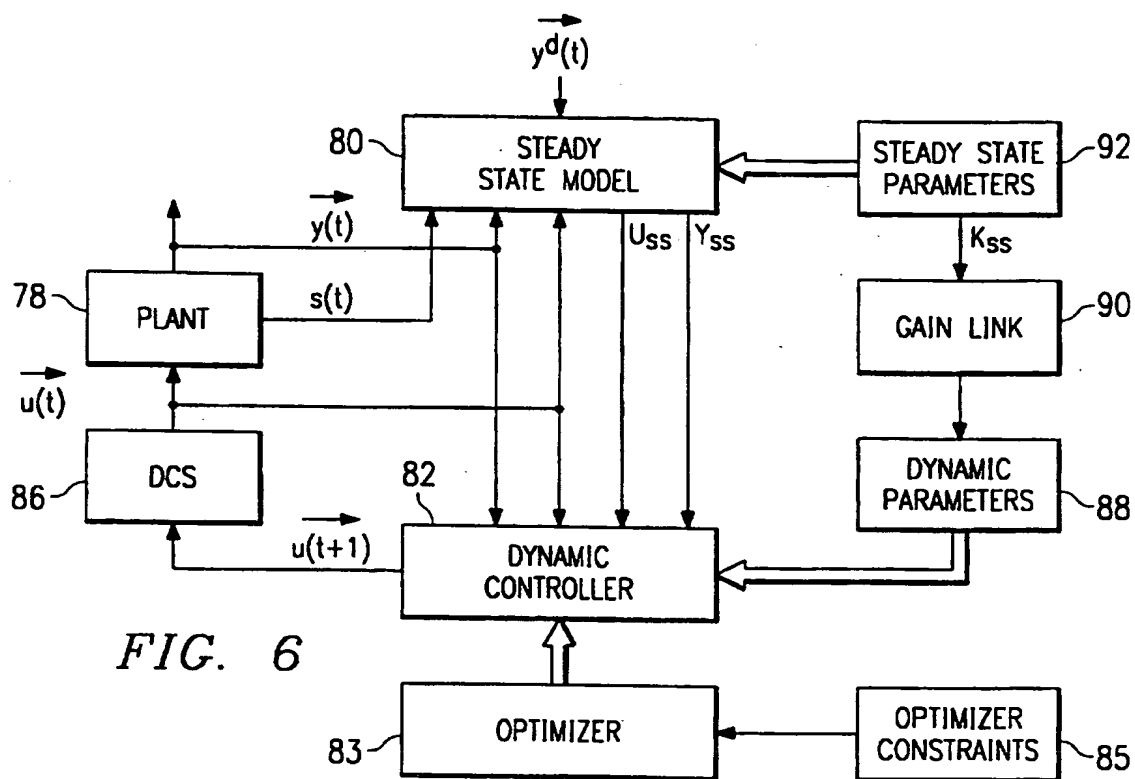


FIG. 6

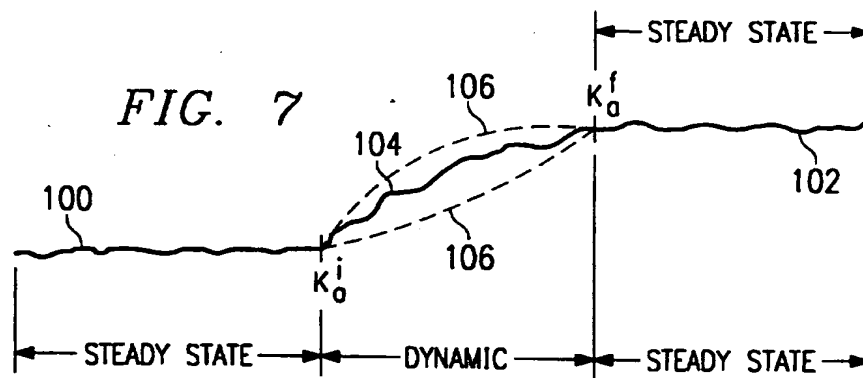


FIG. 7

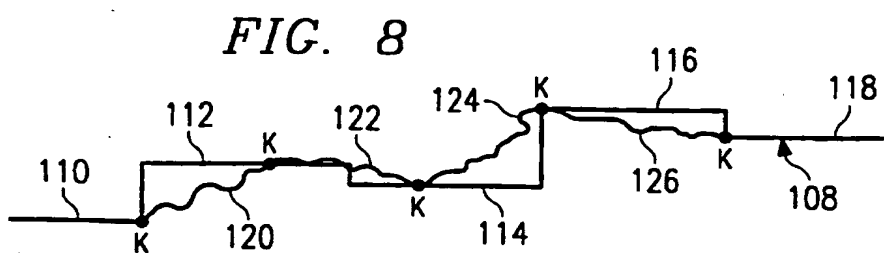


FIG. 8

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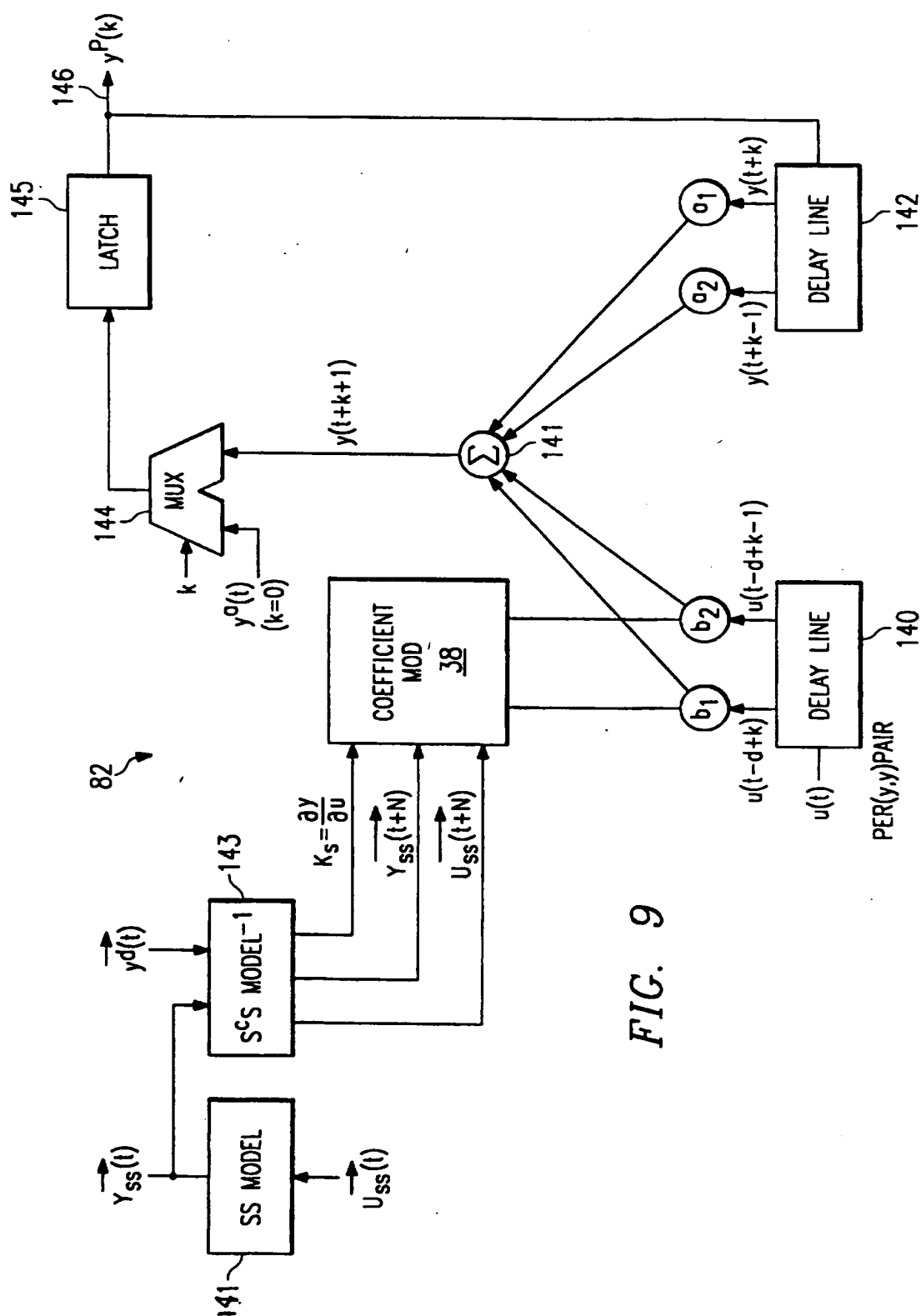
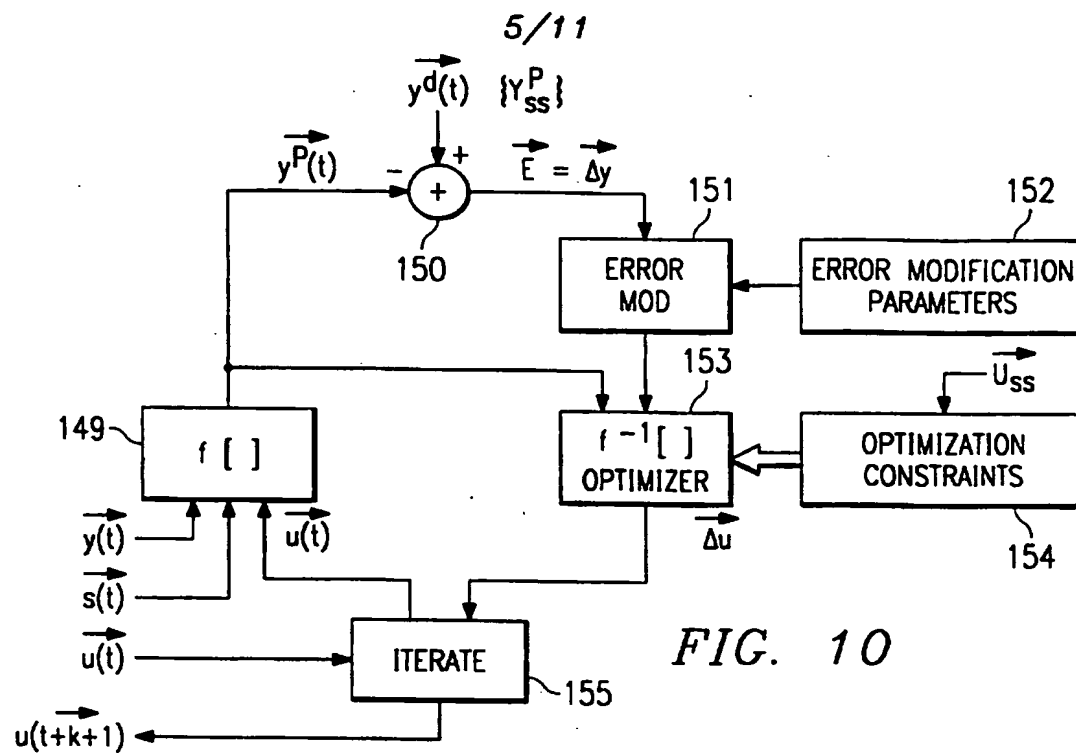
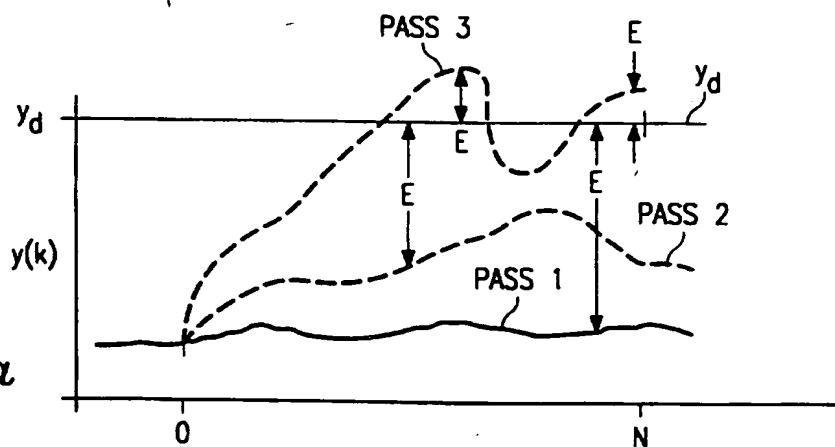


FIG. 9

**FIG. 11a****FIG. 11b**